

NASW-98016 Final Technical Report

29-Jul-1998 to 15-Nov-2002

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Summary

During this period work was performed in the following areas. These areas are defined in the Work Schedule presented in the original proposal.

- BRDF development
- Data acquisition and processing
- THR Table generation
- Presentations and Publications

BRDF Development

BRDF development involves creating and/or modifying a reflectance model of the Antarctic surface. This model must, for a temporal and spatial average, be representative of the East Antarctic plateau and be expressed in terms of the three standard surface angles: solar zenith angle (SolZA), view zenith angle (SatZA), and relative azimuth angle (RelAZ).

We have taken the approach of developing the BRDF model using an empirical model of Antarctic reflectance anisotropy from Warren et. al. (JGR, **103**, 1998). Their parametric model, which is based upon multi-year ground measurements in Antarctica, is only valid down to SolZA=67°. Any BRDF model must cover the full range of angles if it is to be at all useful in radiative transfer calculations. We attempted to augment the Warren model for low solar angles. We began by invoking reciprocity (i.e. requiring the same BRDF when exchanging view angles for illumination angles). This fills some, but not all, of the remaining “angular space.” The remaining unknown BRDF occurs at solar *and* satellite zenith angles less than 67°. Warren et al. presented their measurements by plotting them versus scattering angle (sometimes called phase angle) in order to demonstrate that the data could not be simply parametrized in that single angle. Their plots (in their 1998 paper) demonstrate this point, but only for forward-scattered light. In the backscatter direction (i.e. low solar and satellite zenith angles) a scattering angle parametrization appears reasonably valid. Thus we filled out the BRDF model at low angles using a quadratic parametrization in scattering angle.

Having developed a semi-empirical model of the surface reflectance, we proceeded to validate it with satellite data. This was necessary because a) the model is based upon ground measurements of anisotropy, a combination of surface BRDF and the incident radiance distribution, b) we wish to use the model for satellite measurements and need to know if ground measurements yield the same result, and c) we guessed (an educated guess) the BRDF for a large portion of the angular range. In validating the model, we wished to do more than just compare the model with other measurements. Indeed, we wanted to adjust the model using those comparisons, if necessary. Since the parameterization in the Warren et. al. model (and consequently in ours) is entirely empirical, modifying this model based upon additional data cannot be performed by parametric regression. Another limitation is that, like the ground data, no satellite validation data cover the full range of angles. We therefore chose a non-parametric regression that would revert to our model where data were lacking or poor. The standard approach in atmospheric sciences under such conditions is the Maximum A Posteriori (MAP) method, a.k.a. the Rogers maximum likelihood method (Rogers et. al., *Rev. Geophys.*, **14**, 1976).

In the MAP method, the estimate of geophysical quantities ρ are a combination of measured quantities I_{meas} and a priori quantities I_a according to the following relationship.

$$\rho = \rho_a + \left[S_a^{-1} + K^T S_I^{-1} K \right]^{-1} K^T S_I^{-1} (I_{\text{meas}} - I_a)$$

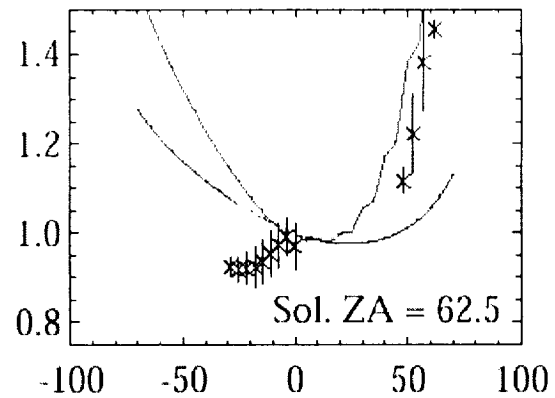
The measurement covariance S_I and the a priori covariance S_a determine, for each quantity ρ , the relative weights of I_{meas} and I_a that contribute. Thus the results are very much dependent upon the uncertainty estimates and their correlations that comprise the covariances. Since the a priori is our model, we used uncertainties of the ground measurements themselves, which we estimate to be 1%. This uncertainty excludes any constant biases in the measurements, as those would not affect measurement of anisotropy. Next, we estimated the uncertainty, using an atmospheric radiative transfer model, due to diffuse scattered radiation just above the surface. This uncertainty accounts for the difference between reflectance anisotropy and BRDF. The error, and hence the uncertainty, is largest at high SolZAs and short wavelengths where the amount of diffuse radiation is substantial.

For measurements we chose Meteor-3 TOMS data. The TOMS, designed to map ozone column amounts, measured radiances at 6 channels between 312.5 nm and 380 nm. These data are unique in that they cover the full 360° range of RelAZ over a relatively short period of time. This occurred because the polar orbit of the Meteor-3 spacecraft precessed with a 212 day period. Since we assume azimuthal symmetry in the surface BRDF, we need only measure over 0° < RelAZ < 180° in order to characterize it. There were 13 such half-periods during the Meteor-3 TOMS data record. We averaged measurement results from these periods in order to obtain the best estimated radiance at the top of the atmosphere (TOA). The number of measurements for each data cell was always fewer than 13 due to the seasonal nature of solar illumination of Antarctica. As with the ground measurements, a constant, systematic bias in the radiances will not affect a measurement of the TOA angular dependence. We therefore estimated the uncertainty of each data cell from the standard deviation of the measurements. Where only 1 measurement was available, we used the standard deviation at the nearest angle with 2 or more entries.

The sensitivity matrix K was computed using our Gauss-Seidel radiative transfer model (RTM). This RTM is described in Herman, et. al., *Appl. Opt.*, **34**, 1995. One advantage is that it is a vector algorithm, meaning it handles polarization correctly. This is necessary for radiation in the UV or near-UV with significant Rayleigh scatter. Another indispensable feature of this model is that it will handle non-Lambertian surface reflectances such as Antarctica. The RTM is used to generate the Jacobian K using perturbations to the existing model. Each element of the matrix relates changes in TOA radiances at a particular viewing condition to changes in surface reflectance at another set of viewing conditions. In order to consider all viewing conditions, K is a 1638×1638 matrix. At 360 nm this matrix is nearly diagonal (sometimes called block diagonal). This means that scattering and absorption in the atmosphere does not significantly affect the direction of the reflected radiation, though it can affect its magnitude.

We began by applying the maximum likelihood approach to TOMS data at 360 nm. Our first discovery was that a priori uncertainties are considerably smaller than those of TOMS. The result is a solution that is always driven to the a priori. We relaxed the a priori uncertainties and found a reflectance distribution much closer to the radiance distribution measured at the TOA. This presented a problem, because the 360 nm radiance distribution appeared altogether unphysical as the reflections approached the principal plane, RelAZ = 0°, 180° (see Figure 1).

Figure 1. TOMS Meteor-3 360 nm radiance data over Antarctica are shown as a function of satellite zenith angle in the principal reflection plane ($\phi = 0^\circ, 180^\circ$). The ordinate is relative signal. Three TOA radiance models are also shown for differing surface reflectances: Lambertian (blue), our empirical model (green), and a highly forward scattering model (red).



The data agreed reasonable well with surface models in the forward direction (positive SatZA in the figure), favoring a highly forward scattering reflectance model. But results in the backward direction (reflection back toward the sun) fit no reasonable range of models. We concluded that the cause of this behavior was instrumental rather than geophysical because

1. no known atmospheric constituent (e.g. aerosols, clouds, cloud shadow) has a scattering phase function that modifies the overall atmospheric scattering in such a way,
2. the backscatter effect disappears, and agrees with other sensors, at RelAZ values more than 10° away from the principal plane, and
3. the measurements are inconsistent with TOMS Meteor-3 measurements of the 331/360 nm radiance ratio.

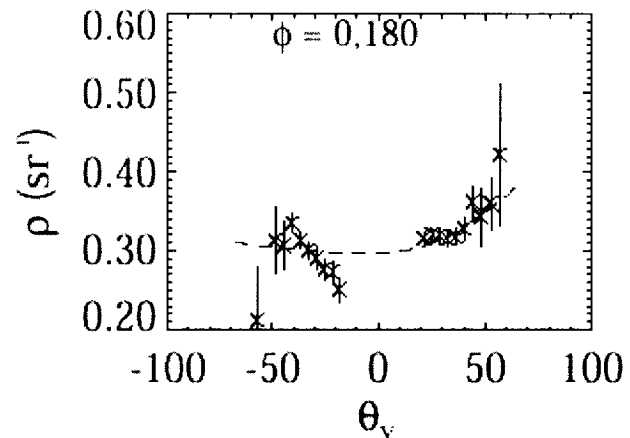
The 331/360 nm radiance ratios gave us the clue that the effect was instrumental. Solar measurements made by TOMS Meteor-3 indicate substantial fluctuations in sensor response during periods when the Meteor-3 orbit lined up with the day/night terminator (corresponding to principal plane reflections). A possible cause was the rapid increase and subsequent decrease in sensor temperature near terminator orbits. Channel ratios of solar data, such as 331/360 nm, exhibited only small changes, indicating wavelength independence of the response variation.

Upon closer examination, we realized that wavelength ratios also contain information about surface properties. This follows from the λ^4 dependence of Rayleigh scattering. Surface characteristics transfer most clearly to the TOA when atmospheric scattering and absorption are at a minimum. Wavelengths in the visible spectrum (VIS) are particularly good for observing Antarctic reflectance for this reason. As the wavelength becomes shorter, Rayleigh scattering begins to dominate the TOA radiance distribution to a point where, eventually, TOA radiances are unaffected by surface properties. Thus a ratio of 300 nm and 600 nm radiances would contain information about surface reflectance (ignoring ozone absorption, of course) even if there were no inherent wavelength dependence in that reflectance. Since the Rayleigh dependence is so steep, we surmised that the difference in scattering between even 331 nm and 360 nm (these two channels are common to several TOMS) would provide adequate surface sensitivity. Indeed they did, having sensitivities about a third of the 360 nm sensitivities. This decrease in sensitivity was made up for by the improved measurement uncertainty resulting from better sensor stability.

We proceeded with a regression of TOMS Meteor-3 331/360 nm data using the MAP method described above. The results appeared much more realistic, as represented by the solution for the principal plane shown in Figure 2. There are clearly some residual problems in the backward scattering direction, so we must conclude that the uncertainty in the TOMS data are insufficient

to independently characterize the surface BRDF. However, the comparisons between the retrievals and our model are good enough, particularly in the forward plane, that we can consider the model validated by the TOMS data.

Figure 2. Antarctica BRDF in the principal reflection plane assuming a total hemispheric reflectance of 97%. Points are derived from a MAP regressoin of TOMS Meteor-3 331/360 nm radiances. The dashed line is our model of the BRDF for the same range of angles.



Data Acquisition and Processing

We successfully acquired a limited amount of NOAA-9 AVHRR data for radiance validation. The data were obtained from the Laboratory for Terrestrial Physics at Goddard Space Flight Center. We developed our own reading and unpacking software, which we used to select Channel 1 data (visible). We then applied geographic subsetting criteria (same as used for TOMS), and wrote only the relevant data to packed binary files. We proceeded with analysis of these data, which is not yet complete.

THR Table generation

The Total Hemispheric Reflectance (THR) table is a table of TOA radiances derived for a specific surface reflectance model. It serves as a substitute for the full radiative transfer model in situations where the RTM is impractical. Our intent is to use these tables to assess the radiometric calibration of various sensors. We wish to investigate the time-dependent calibration as well as the absolute sensor calibrations by comparing with our surface reflectance model. Thus a radiative transfer run to predict TOA radiances is required for each datum. Since the calibration comparisons require a large sample of data, direct use of the RTM is prohibitively time consuming. Rather, we created a look-up table where the nodes are calculated radiances at specific viewing conditions. Upon reading actual measurements, interpolation is used to find the calculated radiance corresponding to the specific conditions of the measurement.

We began with the table look-up software used for Version 8 TOMS ozone retrievals. Several look-ups are performed in these retrievals, beginning with a determination of the effective surface reflectance. A second look-up is used to find the column ozone amount by interpolating on radiances between two ozone node values. The TOMS retrievals perform a final look-up with the known ozone column amount to compute expected radiances at additional channels. These are called radiance residues because they are a measure of the radiance inconsistency when multiple ozone-sensitive wavelengths are used. We modified this third and final look-up specifically for Antarctic radiance look-ups. We assumed that the THR was 97% and that column ozone is known. Software modification was required because TOMS retrievals assume Lambertian surface reflectance. This means the TOA radiances can only vary with SolZA and SatZA, and are invariant with RelAZ. We inserted these azimuthal angles as an additional

interpolation step.

Our modified table look-up algorithm performs the following interpolations in the order listed.

1. SatZA and SolZA together – Lagrangian interpolation
2. RelAZ – Lagrangian interpolation
3. Column ozone – linear interpolation
4. Surface pressure – linear interpolation

We tested the interpolation by first verifying that it gave the same result as the TOMS table look-up when using the TOMS table. We then generated our table using the Gauss-Seidel RTM described above and the modified empirical surface reflectance model, also described above. We assumed a perfect Rayleigh-scattering atmosphere with no aerosols or clouds. We found interpolation errors below 0.1% when we compared direct RTM results between nodes with table-interpolated results.

The table was computed for 6 different wavelengths: 331 nm, 357 nm, 360nm, 589 nm, 630 nm, and 775 nm. These wavelengths were chosen specifically to match those of TOMS and AVHRR. All wavelengths lists are also available on the GOME instrument. The 589 nm and 775 nm wavelengths were specifically chosen as ones where the ozone absorption cross sections are the same as 331 nm and 357 nm, respectively.

Presentations and Publications

We presented our approach and initial results for assessing sensor radiometric calibrations at the 2000 COSPAR conference. This oral presentation was a general outline of the process.

We presented preliminary results of our Antarctic BRDF determination at The Third International Workshop on Multiangular Measurements and Models in 2002. Those results, essentially those described above in our description of BRDF development, were in a poster presentation.

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